A Single-Phase Hybrid Active Power Filter using Extension p-q Theorem for Photovoltaic Application

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Abstract—**This paper presents a single-phase two-wire hybrid active power filter that is used in conjunction with photovoltaic system. The uniqueness of proposed scheme is the fact that it improves the filtering performance of the conventional active power filter, as well as simultaneously supplies the power from the photovoltaic array to the load and distribution system. The current commands derivation is based on the extension instantaneous-reactive power theorem. The proposed scheme is described in detail. It will primarily focus on the power circuit, the compensation current reference derivation, and the passive high-pass filter design. Experimental results obtained from a laboratory system that verifies the viability and effectiveness of the proposed scheme are presented.**

Keywords-extension p-q theorem; hybrid active power filter; photovoltaic; power electronics

I. INTRODUCTION

Due to the proliferation of nonlinear and switching loads from power electronics converters, there is an increasing concern to control and reduce the harmonics current in distribution power lines [1]. These types of loads draw nonsinusoidal currents from the mains, causing power quality (PQ) problems.

The passive filtering is the simplest solution to mitigate the harmonics problem. Although simple, the passive filter is large, heavy and bulky [2], [3]. The passive filter is known to cause resonance, thus affecting the stability of the power systems. As the regulatory requirements become more stringent, the passive filter might not meet future revisions of a particular Standard.

Remarkable progress in power electronics had spurred interest in active power filter (APF) for harmonics mitigation. The basic principle of APF is to utilize power electronics technologies to produce harmonics current components that cancel the harmonics current components from the nonlinear loads. Previously, majority of the controllers developed for APF are based on analog circuits [4], [5]. As a result, the APF is inherently subjected to signal drift. Digital controller using digital signal processor (DSP) or microprocessor is preferable, primarily due to its flexibility and immunity to noise [6], [7]. However it is known that using digital methods, the high order harmonics are not filtered effectively and the switching ripples remain in the source current. This is due to the time and phase delay in digital controller.

The idea of hybrid APF has been proposed by several researchers [8]-[10]. In this scheme, a passive filter is used in addition to a conventional APF. The main purpose of the passive filter is to improve the damping performance of high-order harmonics.

Recently, there is an increasing concern about the environment pollution. The need to generate pollution-free energy has triggers considerable effort toward renewable source of energy [11]. Solar energy, in particular, is a promising option. Efforts have been made to combine the APF with photovoltaic (PV) system [12]-[14]. However, it appears that no attempt has been made to combine a hybrid APF with PV system.

In this paper, a new variation of a hybrid APF is developed. We propose a hybrid APF topology for a single-phase two-wire system, connected to a PV array. The proposed topology is unique because it effectively filters harmonics current less than 1 kHz and of higher frequency. Furthermore, it simultaneously supplies the power from the PV array to the load and the distribution. The main contribution of this work is the application of the extension instantaneous-reactive power (p-q) theorem to derive the compensation current reference for this topology. Although the derivation of current reference based on extension p-q theorem is not new [13]-[15], this approach has not yet being applied to a single-phase two-wire hybrid APF system involving passive high-pass filter (HPF), APF and PV array. Using the extension p-q theorem, the resulting equations for the reference current of single-phase two-wire system is simpler compared with the p-q theorem presented in [16].

This paper will describe the proposed hybrid APF with PV system. It will primarily focus on the power circuit, the compensation current reference derivation, and the passive HPF design. Finally, the experimental results that verify the theoretical predictions of the proposed configuration will be presented.

II. PRINCIPLE OF OPERATION

Fig. 1 presents the proposed hybrid APF with PV system block diagram, connected in parallel with a nonlinear load. It consists of a passive HPF, a single-phase APF constructed using a full-bridge voltage source inverter (VSI) and PV array.

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The VSI and the PV array are connected in parallel with the DC-bus capacitor. In the proposed scheme, the low-order harmonics are compensated using the shunt APF, while the high-order harmonics are filtered by the passive HPF. It is envisaged that this configuration is effective to improve the filtering performance of high-order harmonics, thus achieving wideband harmonic compensation.

The VSI is operated in the current-controlled mode (CCM). Furthermore, the proposed hybrid APF with PV system is connected with the distribution line at the point of common coupling (PCC) through a filter inductor, allowing the reactive power control. Fig. 2 shows the control system for the proposed hybrid APF with PV system. The compensated source current is desired to be sinusoidal to yield a maximum power factor (PF). The extension p-q theorem is introduced to derive the compensation current reference.

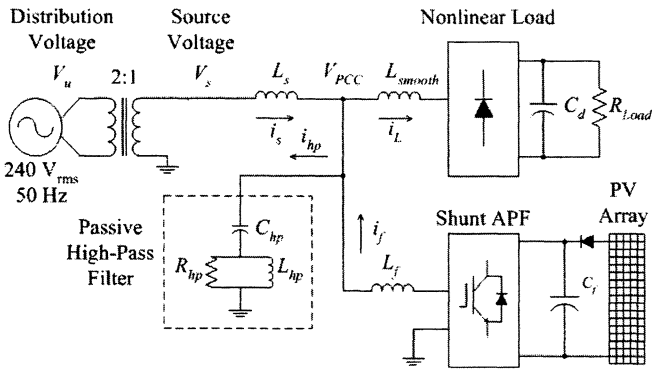


Figure 1. Configuration of the proposed hybrid APF with PV system.

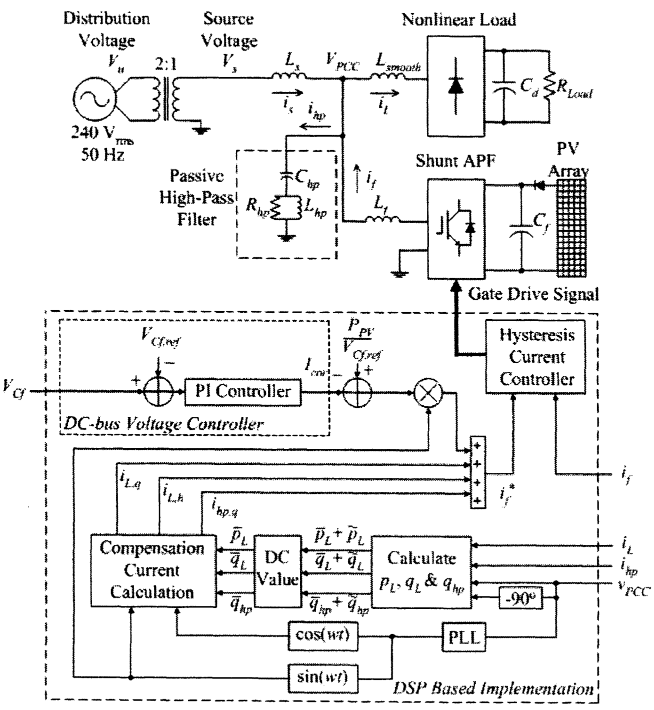


Figure 2. Overall system configuration and control block diagram.

In order to generate the compensation current that follows the current reference, the fixed-band hysteresis current control method is adopted. The aim is to inject the reactive and harmonics currents of the nonlinear load and the reactive current of the passive HPF. Furthermore, a current must be drawn from the distribution source to maintain the voltage across the DC-bus capacitor to a value that is higher than the amplitude of the source voltage. A proportional-integral (PI) controller is implemented for the DC-bus capacitor voltage control. Under the normal operation, the PV array will provide active power to the load and the distribution. However, under no PV power generation condition, the distribution source supplies the active power to the load directly.

A. *Derivation of Compensation Current Reference*

Compensation current reference derivation for the single-phase two-wire APF based on extension p-q theorem has been presented in [14]. In this work, the application of the theorem is further extended to a single-phase two-wire hybrid APF with PV system. The compensation current reference derivation for the proposed scheme is presented in [17]. The extension p-q theorem is adopted for the derivation of active, reactive and harmonics components of nonlinear load current and the reactive component of passive HPF current.

For a single-phase two-wire system with nonlinear load, the load current can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} \sqrt{2} I_{L,n} \sin(n\omega t + \theta_n). \tag{1}$$

Under normal circumstances, the voltage at PCC can be assumed to be a sinusoidal, i.e.,

$$v_{PCC}(t) = \sqrt{2} V_{PCC} \sin(\omega t + \phi). \tag{2}$$

The HPF current can be represented as

$$i_{hp}(t) = \sqrt{2} I_{hp,n} \sin(\omega t + 90^\circ). \tag{3}$$

Therefore, the instantaneous active power of nonlinear load can be calculated as

$$\begin{aligned} p_L(t) &= v_{PCC}(t) \cdot i_L(t) \\ &= \bar{p}_L + \tilde{p}_L. \end{aligned} \tag{4}$$

The instantaneous reactive power of nonlinear load can be written as follows

$$\begin{aligned} q_L(t) &= v'_{PCC}(t) \cdot i_L(t) \\ &= \bar{q}_L + \tilde{q}_L. \end{aligned} \tag{5}$$

The instantaneous reactive power of HPF can be calculated as

$$q_{hp}(t) = v'_{PCC}(t) \cdot i_{hp}(t)$$
$$= \bar{q}_{hp} + \tilde{q}_{hp}, \quad (6)$$

where $\bar{p}_L$, $\bar{q}_L$ and $\bar{p}_{hp}$ represent the constant part, $\tilde{p}_L$, $\tilde{q}_L$ and $\tilde{p}_{hp}$ denote the variant component, and $v'_{PCC}(t)$ denotes the PCC voltage shifted by $90°$.

By obtaining the constant part in (4), (5) and (6), the active ($i_{L,p}$), reactive ($i_{L,q}$) and harmonics ($i_{L,h}$) components of nonlinear load current and the reactive ($i_{hp,q}$) component of the passive HPF current can be readily calculated as follows:

$$i_{L,p}(t) = \sqrt{2}\frac{\bar{p}_L}{V_{PCC}}u(t), \quad (7)$$

$$i_{L,q}(t) = \sqrt{2}\frac{\bar{q}_L}{V_{PCC}}u(t - 90°), \quad (8)$$

$$i_{L,h}(t) = i_L(t) - i_{L,p}(t) - i_{L,q}(t), \quad (9)$$

and

$$i_{hp,q}(t) = \sqrt{2}\frac{\bar{q}_{hp}}{V_{PCC}}u(t - 90°), \quad (10)$$

where $u(t)$ is a unit vector in phase with the PCC voltage.

Finally, the compensation current reference can be expressed as

$$i_f^* = i_{L,q} + i_{L,h} + i_{hp,q} - I_{Cf} \cdot u(t) + \frac{P_{PV}}{V_{Cf,ref}} \cdot u(t), \quad (11)$$

where P_{PV} is the active power of PV array, I_{Cf} is the DC-bus capacitor charging current, and $V_{Cf,ref}$ is DC-bus capacitor voltage reference.

B. Design of Passive High-Pass Filter

The second-order damped series resonant type HPF topology is adopted in the proposed hybrid APF with PV system. The HPF consists of a capacitor C_{hp}, inductor L_{hp} and an inductor bypass resistor R_{hp}. Fig. 3 presents an equivalent circuit of the proposed hybrid APF system for harmonics, where Z_{hp} is the equivalent impedance of HPF and Z_s is the equivalent source impedance assumed to be a simple inductor. In Fig. 3, the shunt APF is assumed to act as an ideal current source which produces the compensation current that follows the current reference, while the nonlinear load is considered as a harmonics current source.

Since we are only interested in the system performance with the harmonics components, we can neglect the source voltage. This is because the source voltage is assumed to contain only the fundamental frequency component.

A generalized transfer function approach to harmonic filter design has been presented in [18]. This method is based on the Laplace transform and superposition. In this work, the transfer function approach to harmonic filter design is adopted for the passive HPF design. The HPF impedance transfer function $H_{hp}(s)$ can be derived in normalized form as

$$H_{hp}(s) = Z_{hp}(s) = \frac{A}{s\left(\frac{s}{\omega_p}+1\right)} \cdot \left[\left(\frac{s}{\omega_o}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_o}\right) + 1\right]. \quad (12)$$

In (12),

$$A = \frac{1}{C_{hp}},\ \omega_o = \frac{1}{\sqrt{L_{hp}C_{hp}}},\ \omega_p = \frac{R_{hp}}{L_{hp}},\ Q = R_{hp}\sqrt{\frac{C_{hp}}{L_{hp}}},$$

where A is the gain coefficient, ω_o is the series resonant frequency, ω_p is the pole frequency, and Q is the quality factor.

The passive HPF is tuned to the resonant frequency of 1.28 kHz ($f_o = \frac{1}{2\pi\sqrt{L_{hp}C_{hp}}}$ = 1.28 kHz). This resonant frequency value is chosen as the filtering performance of the APF is impaired above this frequency.

Depending on the value selected for the inductor bypass resistor R_{hp}, many different transfer function characteristics are possible. The inductor bypass resistor R_{hp} is chosen based on the desired high-pass response and the series resonant attenuation. The quality factors of $0.5 \le Q \le 2.0$ are typical.

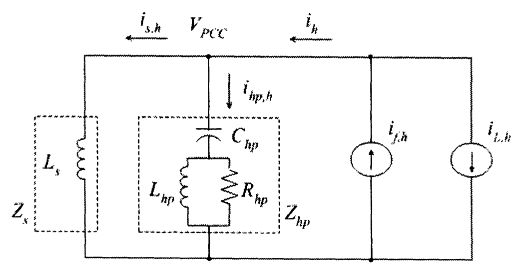


Figure 3. Simplified model of the hybrid filter.

Higher Q factors allow more series resonant attenuation and less high-pass. By contrast, lower Q factors provide less series resonant attenuation and greater high-pass response. Hence, the proper selection of Q is essentially required to satisfy the series resonant and high-pass response performances. In this work, the Q factor was selected as 0.69, considering the required high-pass response over a wide frequency band.

After the hybrid APF with PV system is configured and $Z_{hp}(s)$ is known, the distribution system current to injected current transfer function $H_{cds}(s)$ can be derived for the hybrid APF with PV system connected to the PCC as

$$H_{cds}(s)=\frac{i_{s,h}(s)}{i_h(s)}=\frac{Z_{hp}(s)}{Z_{hp}(s)+Z_s(s)}. \qquad (13)$$

Transfer function (13) is important because it can be used to assess the overall system performance.

A bode magnitude plot of $H_{cds}(s)$ is shown in Fig. 4 where it has one crest due to the parallel resonance between $L_s + L_{hp}$ and C_{hp}. In particular, the parallel resonance is a problem, as it enlarges harmonics around the parallel resonant frequency ($f_r = \frac{1}{2\pi\sqrt{(L_s + L_{hp})C_{hp}}}$ = 1.07 kHz). This crest can be minimized by selecting the value of Q factor close to 0.7. For the plot shown in Fig. 4, the distribution system current to injected current transfer function $H_{cds}(s)$ can be evaluated at low and high frequencies. For low frequencies, it has a 0 dB gain from 0 Hz to the parallel resonant frequency f_r. At f_r the gain is determined by the selection of Q. For high frequencies, the roll-off of the high frequency components above the parallel resonant frequency f_r is -20 dB per decade. Hence, the harmonics filtering is divided between the two filters: the low-order harmonics are compensated using the shunt APF, while the high-order harmonics are filtered by the passive HPF.

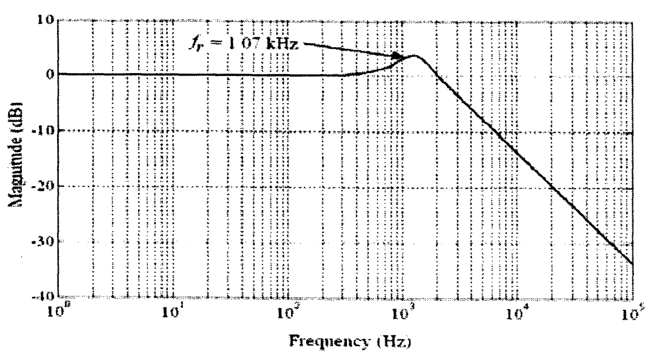


Figure 4. Bode magnitude diagram of the transfer function $H_{cds}(s)$ for the proposed hybrid APF system.

III. Experimental Results

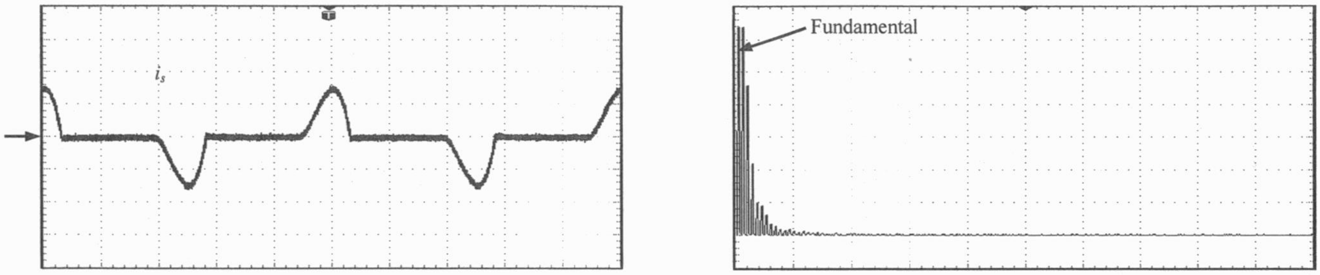
The proposed hybrid APF system was tested in the laboratory with a low-power experimental prototype. The system parameters are shown in Table I. For the experimental system, the leakage impedance of the transformer is assumed to be the source impedance, L_s = 0.76 mH. The passive HPF is tuned to the resonant frequency of 1.28 kHz. The design parameters of the HPF are: L_{hp} = 1.76 mH, C_{hp} = 8.8 μF and R_{hp} = 10 Ω. A diode rectifier with a DC-link capacitor C_d and a smoothing inductor L_{smooth} was used as the load. The control system was implemented using a dSPACE DS1104 DSP board.

The source current waveform and its harmonics spectra without compensation are shown in Fig. 5. As can be seen, the source current is highly distorted. Fig. 6 presents the source current waveform with basic shunt APF. From the spectra, it can be observed that for the basic APF the source current contains appreciable amount of high-order harmonics. The harmonics are effectively filtered by the proposed scheme, as depicted by Fig. 7. The total harmonic distortion calculated up to 10 kHz ($THD_{10\,kHz}$) is reduced from 130 % to 36 % using the basic shunt APF. With the proposed scheme, the $THD_{10\,kHz}$ is further reduced to 19 %.

Fig. 8 shows the performance of the proposed hybrid APF with a PV array during normal operation. Fig. 8(a) shows the load current and compensated source current waveforms with no active power generation from PV array. The active power is provided by the distribution line directly. Fig. 8(b) shows the load current and compensated source current waveforms with 175 W active power generation from PV array. The experimental results obtained show that the generated PV power is provided to the load and distribution through the proposed hybrid APF system.

TABLE I. Experimental System Parameters

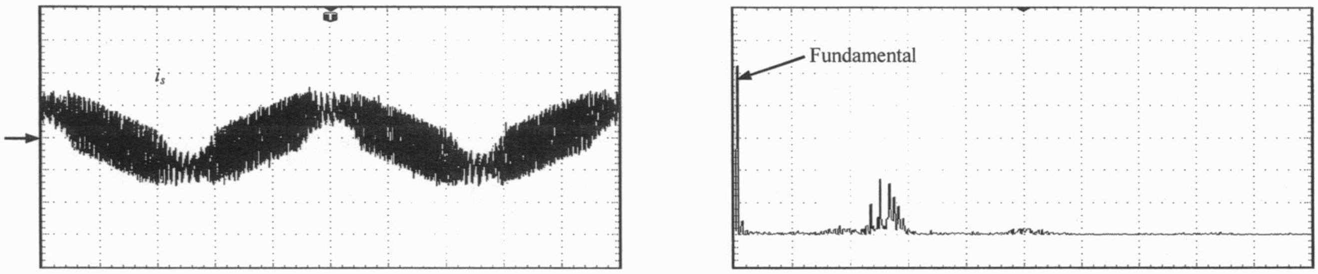
Distribution Voltage	V_u = 240 V_{rms} (50 Hz)
Source Inductance	L_s = 0.76 mH
Rectifier DC-link Capacitor	C_d = 1000 μF
Rectifier Smoothing Inductor	L_{smooth} = 1.15 mH
Maximum Switching Frequency	$f_{sw,max}$ = 10 kHz
Hysteresis Current Control Band	H = 1.0 $A_{peak\text{-}to\text{-}peak}$
APF Inductor	L_f = 10.0 mH
APF DC-bus Capacitor	C_f = 1000 μF
DC-bus Capacitor Voltage Reference	$V_{Cf,ref}$ = 250 V_{dc}
HPF Inductor	L_{hp} = 1.76 mH
HPF Capacitor	C_{hp} = 8.8 μF
HPF Resistor	R_{hp} = 10 Ω
Load Resistor	R_L = 250 Ω



Load Resistance, $R_L = 250\ \Omega$ Load Resistance, $R_L = 250\ \Omega$

(a) Scales: source current 1A/div, time 4ms/div. (b) Scales: spectra 50mA/div, frequency 1.25kHz/div.

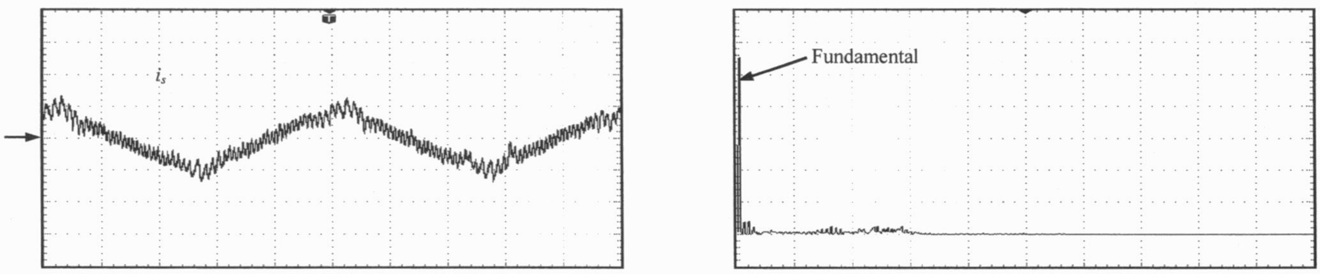
Figure 5. Experimental results without compensation, (a) source current waveform and (b) source current spectra.



Load Resistance, $R_L = 250\ \Omega$ Load Resistance, $R_L = 250\ \Omega$

(a) Scales: source current 1A/div, time 4ms/div. (b) Scales: spectra 100mA/div, frequency 1.25kHz/div.

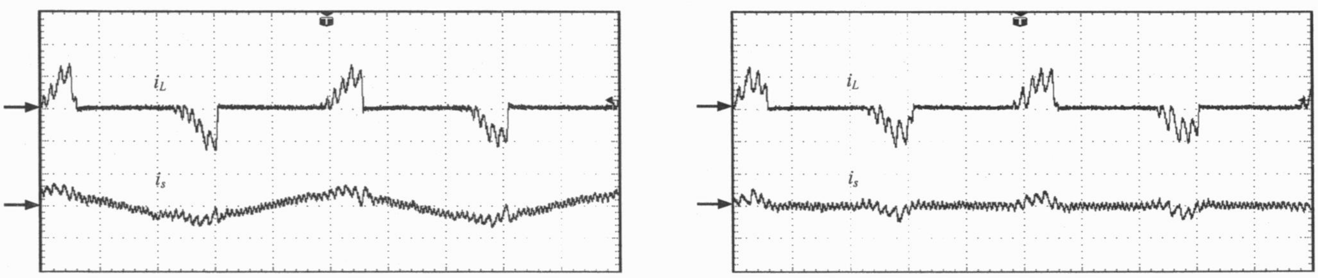
Figure 6. Experimental results with basic shunt APF, (a) source current waveform and (b) source current spectra.



Load Resistance, $R_L = 250\ \Omega$ Load Resistance, $R_L = 250\ \Omega$

(a) Scales: source current 1A/div, time 4ms/div. (b) Scales: spectra 100mA/div, frequency 1.25kHz/div.

Figure 7. Experimental results with proposed scheme, (a) source current waveform and (b) source current spectra.



Load Resistance, $R_L = 250\ \Omega$ Load Resistance, $R_L = 250\ \Omega$

(a) Scales: load current 2A/div, source current 2A/div, time 4ms/div. (b) Scales: load current 2A/div, source current 2A/div, time 4ms/div.

Figure 8. Experimental results with proposed APF with PV system, (a) load and source current waveforms with no PV power generation and (b) load and source current waveforms with 175 W PV power generation.

IV. Conclusion

A single-phase two-wire hybrid APF that interconnects to the PV system is presented. The proposed scheme combines the APF with a passive filter to improve the filtering performance of high-order harmonics. The derivation of compensation current reference is simpler with the utilization of extension p-q theorem. The experimental results show the effectiveness of the proposed scheme for wideband harmonics compensation and PV power handling capability.

References

[1] H. Akagi, "New trends in active filters for power conditioning," IEEE Trans. on Industry Applications, vol. 32, no. 6, pp. 1312-1322, Nov.-Dec. 1996.

[2] D. Sutanto, M. Bou-rabee, K. S. Tam, and C. S. Chang, "Harmonic filters for industrial power systems," in Proc. IEE International Conference on Advances in Power System Control, Operation and Management, APSCOM, 1991, Hong Kong, vol. 2, pp. 594-598.

[3] J. C. Das, "Passive filters – potentialities and limitations," IEEE Trans. on Industry Applications, vol. 40, no.1, pp. 232-241, Jan.-Feb. 2004.

[4] H. L. Jou, J. C. Wu, and H. Y. Chu, "New single-phase active power filter," in Proc. IEE Electric Power Applications, vol. 141, no. 3, pp. 129-134, May 1994.

[5] C. Y. Hsu, and H. –Y. Wu, "A new single-phase active power filter with reduced energy-storage capacity," in Proc. IEE Electric Power Applications, vol. 143, no. 1, pp. 25-30, Jan. 1996.

[6] S. G. Jeong and M. H. Woo, "DSP-based active power filter with predictive current control," IEEE Trans. on Industrial Electronics, vol. 44, no. 3, pp. 329-336, June 1997.

[7] S. Buso, L. Malesani, P. Mattavelli, and R. Veronese, "Design and fully digital control of parallel active power filters for thyristor rectifiers to comply with IEC-1000-3-2 standards," IEEE Trans. on Industry Applications, vol. 34, no. 3, pp. 508-517, May-June 1998.

[8] S. Fukuda and T. Endoh, "Control method for a combined active filter system employing a current source converter and a high pass filter," IEEE Trans. on Industry Applications, vol. 31, no. 3, pp. 590-597, May-June 1995.

[9] S. Khositkasame and S. Sangwongwanich, "Design of harmonic current detector and stability analysis of a hybrid parallel active filter," in Proc. Power Conversion Conference, PCC, 1997, Nagaoka, Japan, vol. 1, pp. 181-186.

[10] M. Routimo, M. Salo, and H. Tuusa, "A novel control method for wideband harmonic compensation," in Proc. IEEE International Conference on Power Electronics and Drive Systems, PEDS, 2003, Singapore, vol. 1, pp. 799-804.

[11] S. R. Bull, "Renewable energy today and tomorrow," in Proc. of the IEEE, vol. 89, no. 8, pp. 1216-1226, Aug. 2001.

[12] S. Kim, G. Yoo, and J. Song, "A bifunctional utility connected photovoltaic system with power factor correction and U.P.S. facility," in Proc. IEEE Photovoltaic Specialist Conference, 1996, Washington, USA, pp. 1363-1368.

[13] Y. Komatsu, "Application of the extension pq theory to a mains-coupled photovoltaic system," in Proc. Power Conversion Conference, PCC, 2002, Osaka, Japan, vol. 2, pp. 816-821.

[14] T. –F. Wu, C. –L. Shen, C. H. Chang, and J. –Y. Chiu, "1/spl phi/ 3W grid-connection PV power inverter with partial active power filter," IEEE Trans. on Aerospace and Electronic Systems, vol. 39, no. 2, pp. 635-646, April 2003.

[15] Y. Komatsu and T. Kawabata, "Characteristics of three phase active power filter using extension pq theory," in Proc. IEEE International Symposium on Industrial Electronics, ISIE, 1997, Guimaraes, Portugal, vol. 2, pp. 302-307.

[16] B. Dobrucky, H. Kim, V. Racek, M. Roch, and M. Pokorny, "Single-phase power active filter and compensator using instantaneous reactive power method," in Proc. Power Conversion Conference, PCC, 2002, Osaka, Japan, vol. 1, pp. 167-171.

[17] P. C. Tan and Z. Salam, "A new single-phase two-wire hybrid active power filter using extension p-q theorem for photovoltaic application," in Proc. National Power and Energy Conference, PECon, 2004, Malaysia, pp. 126-131.

[18] J. K. Phipps, "A transfer function approach to harmonic filter design," IEEE Industry Applications Magazine, vol. 3, no. 2, pp. 68-82, Mar.-Apr. 1997.